AD-A034 677   HUGHES RESEARCH LABS MALIBU CALIF   F/G 20/6

THIN FILM OPTICAL SWITCH.(U)

NOV 76 B CHEN, G TANGONAN   N00173-76-C-0113

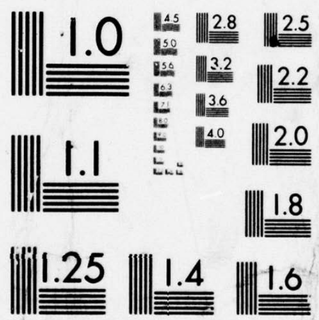
UNCLASSIFIED   NL

| OF |

AD
A034677

END

DATE
FILMED
2-77



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

12

THIN FILM OPTICAL SWITCH

Bor Chen and Gregory Tangonan

Hughes Research Laboratories
3011 Malibu Canyon Road
Malibu, CA 90265

November 1976

Contract N00173-76-C-0113
Quarterly Technical Report 3
For Period 22 July 1976 through 21 October 1976

Sponsored By
NAVAL RESEARCH LABORATORY
4555 Overlook Avenue, S.W.
Washington, DC 20375

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER no.
4. TITLE (and Subtitle) 6 THIN FILM OPTICAL SWITCH.		5. TYPE OF REPORT & PERIOD COVERED 9 Quarterly Report 3, 22 July 76 - 21 Oct 76
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) 10 Bor/Chen ~~and~~ Gregory/Tangonan		8. CONTRACT OR GRANT NUMBER(s) 15 N00173-76-C-0113
9. PERFORMING ORGANIZATION NAME AND ADDRESS Hughes Research Laboratories 3011 Malibu Canyon Road Malibu, CA 90265		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS Naval Research Laboratory 4555 Overlook Ave., S.W. Washington, DC 20375		12. REPORT DATE 11 November 1976
		13. NUMBER OF PAGES 18
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office) 12 19p.		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

DISTRIBUTION STATEMENT A
Approved for public release;
Distribution Unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Integrated optics, Optical channel waveguide, Optical switch, Taper coupler

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

During the third quarter of this program, the measurement of single mode coupling efficiency for linear tapers of four different taper lengths was continued. For TM wave propagation, the coupling efficiency was much lower than for TE wave propagation. The difference in coupling efficiency was due to the presence of Li_2O out-diffusion waveguide modes, which occurred only when the TE mode was excited in Ti-diffused channel guide. Because the throughput of linear tapers

next page

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

UNCLASSIFIED 172600

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

LB

for both TE and TM waves were not as high as the 90% required throughput, several design modifications were made. Instead of expanding the 4 μm channel waveguide to 70 μm width, a lower value of 30 μm was used. The linear taper was also replaced with a curved horn of three linear segments of different slopes with the attempt to maximize the coupling efficiency for a fixed coupling length. The channel guide width is expanded from 4 μm to 10 μm by the first linear taper of length 200 μm, from 10 μm to 20 μm by the second linear taper of length 500 μm, and from 20 μm to 30 μm by the third taper of length 800 μm. The full angles of these tapers are 1.72°, 1.15°, and 0.72°, respectively. To ensure an efficient Bragg deflection between two channel waveguides intersecting at the Bragg angle, the grating periodicity was reduced from the original design of 7.0 μm to 4.0 μm. This 4 μm spacing grating is readily achieved by conventional photolithography. The preliminary experimental results of the new taper waveguides indicate that a single mode to single mode coupling efficiency of 90% per taper for TM waves has been achieved.

cont.

The coupling efficiency of a given taper structure depends strongly on the expansion ratio of the channel width (final width to initial channel width). So it is important to know the amount of lateral diffusion which proceeds simultaneously with he downward diffusion. We have studied the Ti concentration profile near the edge of a stripe of 70 ~~μm~~ microns initial width using electron microprobe technique. The lateral spread of this 70 ~~μm~~ microns wide channel guide was about 6 μm on each side. We concluded that enhanced lateral diffusion was not observed in this study.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

PREFACE

The following personnel contributed to the research work reported here: B. U. Chen, G. L. Tangonan, and A. Lee. The photomasks were fabricated by the photolithographic services of Hughes Aircraft Company, Fullerton, California, under the direction of W. Gray and G. Bair.

I. INTRODUCTION

Optical communications is emerging as a new technology which promises significant cost and performance advantages for a wide range of military information transfer systems, particularly airborne and tactical communications. The use of optical fiber transmission circuits provides significant reductions in weight and size, elimination of electromagnetic interference and greater bandwidth over electrical systems. An area of optical communications to which little research has been directed is optical communication switching. The ultimate objective of this research is the development of wideband switch capability, based on optical techniques, for switching optical signals in a communications network.

The program goals involve the design and fabrication of an optical switch based on the deflection of two-dimensionally-confined beams by a voltage-controlled phase grating. This switch is of the double-pole-double-throw (DPDT) type with a research objective of 80% throughput with minimum cross talk. The switching of optical waveguide channel directions is effected using an electro-optic Bragg phase grating formed by applying a voltage to an interdigital electrode configuration. In order to accommodate coupling to the waveguide input ports from single-mode optical fibers, two narrow (4 μm) single-mode channel waveguides will be used. These will be expanded substantially through tapered sections to wide, multimode waveguides that intersect in the grating interaction region.

II. LINEAR TAPER MEASUREMENT

In the second quarterly report, we described the fabrication of single mode channel waveguides and linear taper structures. The waveguide channels were fabricated on a Y-cut $LiNbO_3$ substrate with the channels aligned parallel to the x-axis. The single mode coupling efficiencies for TE waves propagating through one expansion taper and one contraction taper were reported for four different taper lengths, 300, 600, 900, and 1200 µm. For 1200 µm taper, the coupling efficiencies were 70% at $\lambda = 6328$ Å and 75% at $\lambda = 5145$ Å. In the third quarter of this program, the coupling efficiencies of linear tapers for TM wave were studied. Using the same experimental arrangement as we did for TE wave propagation, TM polarization waves were excited in the 4 µm wide channel section which can support only one TM mode. By comparing the output power of the taper structure with that of the neighboring 4 µm straight channel, the percentage throughput of the structure of one expansion taper and one contraction taper was determined. Table 1 lists the detected output power and taper coupling efficiency for structures on sample 4A when the TM wave was excited.

Figure 1 shows the averaged value of coupling efficiency for both TE and TM waves as a function of the taper length. As shown in the figure, the coupling efficiency for TM wave was much lower than for TE wave. The reason is the following. Lithium and oxygen escaped out of the $LiNbO_3$ substrate when the Ti-in-diffusion process was performed at high temperature. The out-diffusion process resulted in an increase in the extraordinary index of refraction. As a result, in addition to the Ti-in-diffused channel waveguides, there is an additional planar Li_2O out-diffusion waveguide for TE polarization wave when the light propagates in the x-axis. In the TE wave measurement, those out-diffusion modes were coupled out together with the in-diffusion guided mode, hence, a wrong reading of higher output power was obtained. Because the throughput of linear tapers obtained in the experiment is not as high as the 90% required throughput for the optical switch design. A modification of taper dimensions was made.

TABLE 1. Taper Coupling Efficiency Measurement for TM Waves (Sample $LiNbO_3$ 4A)

	Detected Output Power, W	Taper Coupling Efficiency, %
1200 μm taper	1.41×10^{-7}	46
4 μm channel	6.66	—
900 μm taper	0.32	22 20
4 μm channel	8.01	—
600 μm taper	0.49	25 25
4 μm channel	8.10	—
300 μm taper	0.46	24

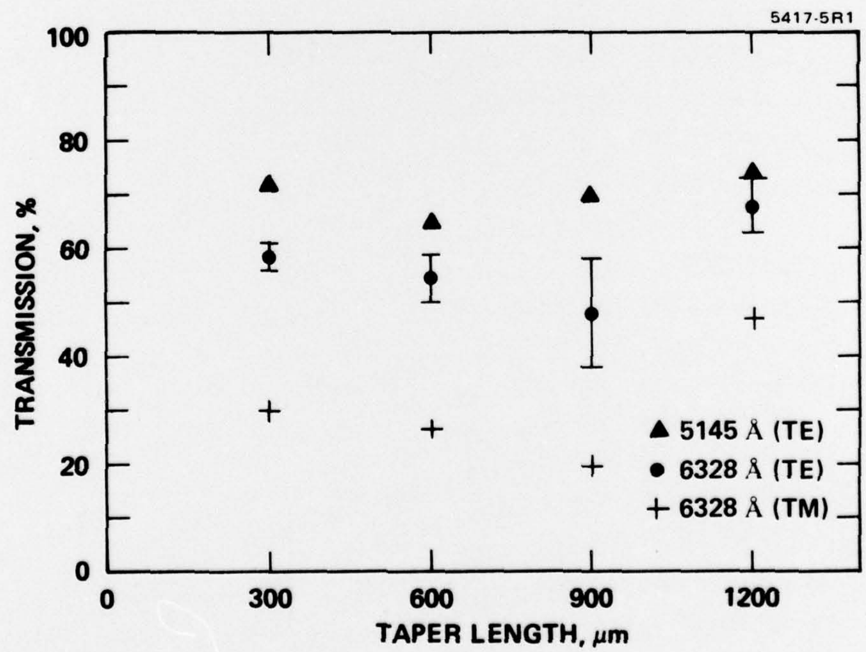


Figure 1. Single mode coupling efficiency of linear tapers as a function of the taper length.

III. MODIFICATION OF SWITCH DESIGN

The impedance transforming horn is well understood in microwave circuit theory. If the taper is sufficiently gentle, radiation will be transmitted adiabatically, continuously readjusting to the slow variation of the transmission line impedance with virtually no reflection or coupling to higher order modes. In reality, one has to sacrifice perfect adiabatic coupling in order to use a taper of reasonable length. The experimental result of single mode transmission measurement showed that linear taper is not an efficient coupler for an expansion ratio of 18 (70/4), even when the taper length is 1200 μm which corresponds to 4000 times the He-Ne laser wavelength in the waveguide. It has been suggested that a given coupling efficiency could be achieved in a shorter length by shaping the walls of the coupler.[2,3] Based on the coupled mode theory, the slope of the coupler can be large when the channel guide width is close to the cutoff width of the higher order modes. Because the wavevector of the first order mode is quite different from the wavevectors of higher order modes, the coupling to higher order modes is small due to phase mismatch. On the other hand, as the width of the coupler increases, the number of higher order modes increases and the phase matching is approached, the slope should decrease.

Because the physical size of the thin-film optical switch is required to be as small as possible (consistent with high optical throughput) a modification of the coupling horn structure is necessary. In order to achieve the goal of 90% single mode transmission efficiency, the width of expanded channel section was reduced from 70 μm to 30 μm and a taper formed out of three linear segments was adopted. Figure 2 shows the new photomask design for single taper waveguide as well as crossed taper waveguide. The taper waveguide structures consist of a 4 μm single mode channel guide section, an expansion taper section, a 30 μm multimode channel guide section, a contraction taper section, and a 4 μm single mode channel guide section. In the photomask, there are also three 4 μm straight channel guides used as the standard for

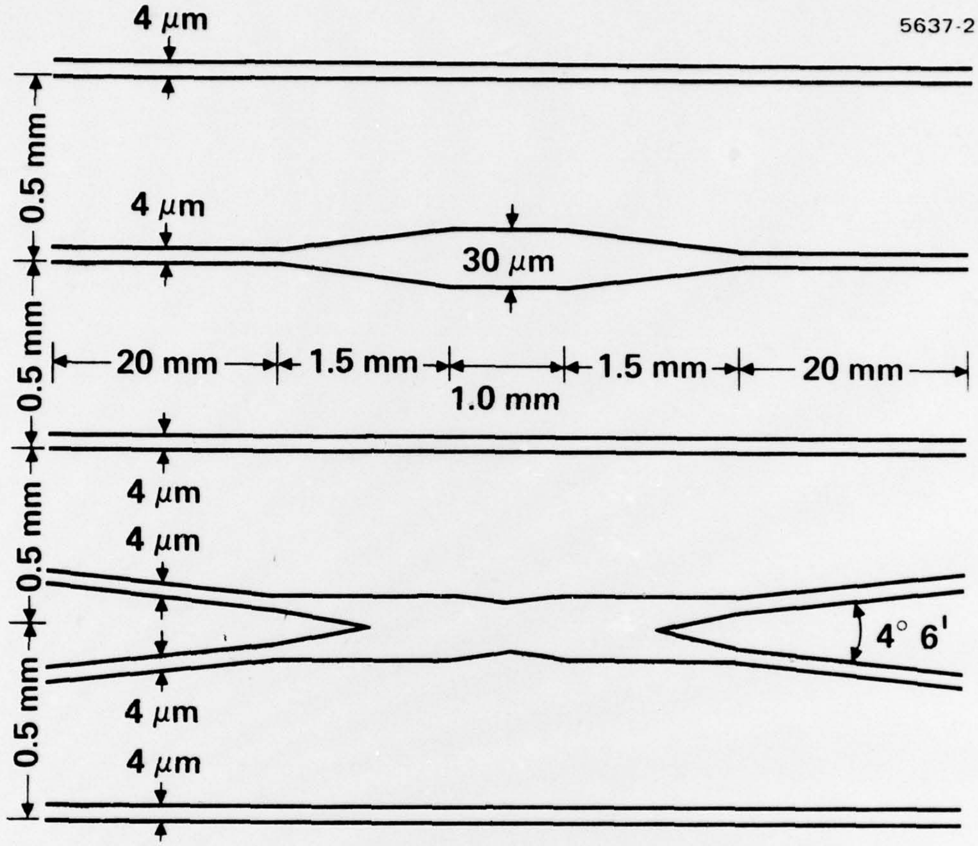


Figure 2. New photomask design for taper waveguides.

taper throughput measurement. The four legs of crossed taper waveguides are bent to parallel to the straight channel guides at a distance of 8 mm from the center of overlapped area. Figure 3 shows the three linear sections of coupling horn structure. The channel waveguide width is expanded from 4 μm to 10 μm by the first linear taper of length 500 μm and from 20 μm to 30 μm by the third linear taper of length 800 μm. The full angles of these tapers are 1.72°, 1.15°, and 0.72°, respectively. The total length of this coupling horn structure is 1.5 mm.

To ensure that Bragg scattering into a well defined direction occurs with optimum efficiency, there must be sufficient number of grating lines that intersected by the beam incident at the Bragg angle, θ_B. As the width of expanded channel section is reduced from 70 μm to 30 μm, the grating design is also changed by reducing the spacing from the original 7 μm to 4 μm. This 4 μm spacing grating is readily achieved by conventional photolithography. In this way, 7.5 periods of interdigital electrodes can be accommodated in the waveguide overlapped area. Because the grating period is smaller, the necessary grating length can also be cut down to 0.5 mm without affecting the value of Q parameter which governs the deflection process. Table 2 lists all the important design parameters for the old and new designs.

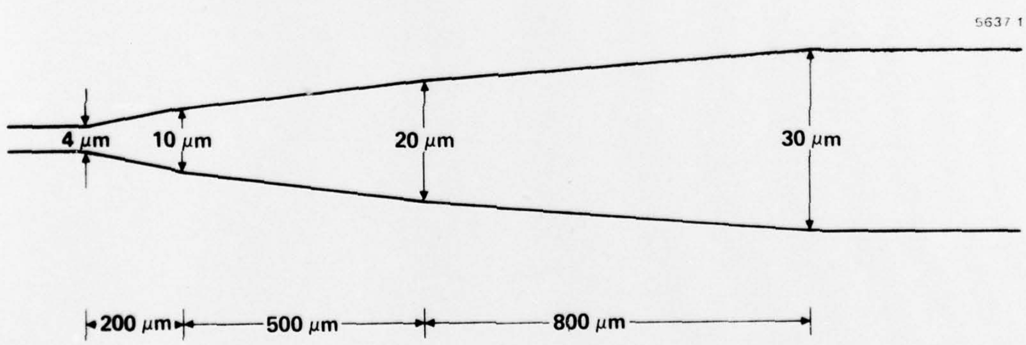


Figure 3. Three linear sections for coupling horn structure.

TABLE 2. Optical Switch Design Parameters

	Old Design	New Design
Width of expanded section, W	70 μm	30 μm
Bragg Deflector: Periodicity, S	7.0 μm	4.0 μm
Bragg Deflector: Length, L	1.7 mm	0.5 mm
Bragg angle, θ_B	1°10'	2°3'
Number of Periods, N	10	7.5
Q parameter, $Q = \dfrac{2\pi\lambda_o L}{n_g S^2}$	20 π	19 π
Device total length, (including coupling tapers)	4.4 mm	4.0 mm

Waveguide structures with the shaped taper design have been fabricated on $LiNbO_3$ substrate (NB 18). The experimental result indicates that a single mode to single mode coupling efficiency of 90% per taper for TM polarization has been achieved. The crosstalk between two intersecting channel guides as a result of the absence of lateral confinement over a portion of the region of intersection was considered as a potential problem. However, no crosstalk was observed to the naked eye when viewing the output modes of crossed tapers.

IV. LATERAL SPREAD OF CHANNEL WAVEGUIDE

Ti-diffused channel waveguides are formed by coating the entire surface of $LiNbO_3$ (or $LiTaO_3$) with titanium using e-beam evaporated and then selectively removing the metal from all the area except the desired channels by the use of photolithographic exposure and subsequent chemical etch. The metal pattern remaining on the surface will then serve as the surface source for diffusion. The fundamental physical property of the diffusion process is that the atoms tend to diffuse from a region of high concentration to that of lower one, at a rate proportional to the concentration gradient between the two regions. The diffusion process proceeds in both lateral (Z-axis) and downward (Y-axis) directions and can be described by the well known second order partial differential equation.

$$\frac{\partial N(y,z)}{\partial t} = D_y \frac{\partial^2 N(y,z)}{\partial y^2} + D_z \frac{\partial^2 N(y,z)}{\partial z^2}$$

where D_y and D_z are diffusion coefficients along y and z directions respectively. The magnitude of D gives a measure of the relative ease or difficulty with which the diffusant can move about in its environment.

The coupling efficiency of a given taper structure depends strongly on the expansion ratio (final width to initial channel width). So it is important to know the amount of lateral diffusion which determines the final diffused channel width. It has been reported that enhanced lateral diffusion,[4] at a rate about 20 times the downward diffusion, for experiments utilizing the diffusion of Nb into Y-cut $LiTaO_3$. We have studied the Ti concentration profile near the edge of a strip of 70 μm initial width using electron microprobe technique. No enhanced lateral diffusion was observed.

Figure 4 shows the result of electron microprobe measurements of a channel guide in sample 5. A focused electron beam was scanned across the surface of a 70 μm wide channel guide at an angle of 19 degrees with respect to the channel edge. The concentration of

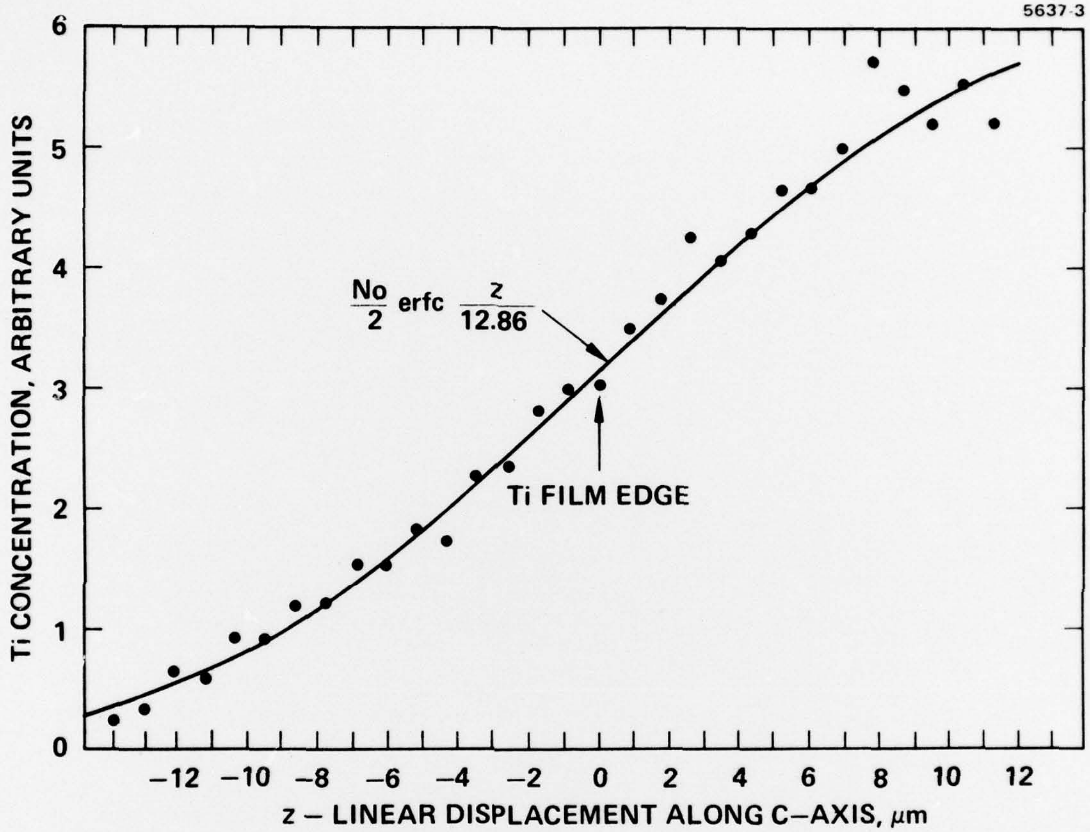


Figure 4. Distribution of Ti near the edge of a stripe of 70 μm initial width.

Ti was measured by the intensity of emitted characteristic X-ray emission of Ti and is plotted in arbitrary units. The penetration depth of the electron beam is estimated to be about 1 μm at the beam energy of 15 keV. The data was taken every 2.5 μm along the scanned path, i.e., 0.83 μm in the direction perpendicular to the edge. There is no known analytical two-dimensional solution for the channel waveguide formed by Ti-diffusion. However, the concentration profile in the Z-axis (C-axis) can be approximated by one-dimension diffusion model. Suppose we can separate the lateral diffusion from the downward diffusion mathematically and assume the initial boundary conditions as

$$\begin{aligned} N &= N_o \qquad Z > 0 \\ N &= 0 \qquad Z < 0 \; . \end{aligned}$$

The resulting particular solution of the one-dimensional diffusion equation can then be expressed as

$$N = \frac{N_o}{2} \operatorname{erfc}\left(\frac{Z}{2\sqrt{D_z t}}\right)$$

where N_o is the initial surface concentration and t is the total diffusion time. The solid curve in Figure 4 is a complementary error function with the parameter of diffusion depth $2\sqrt{D_z t}$ adjusted to give the best fit. The diffusion constant of Ti in C-axis is then given by

$$\begin{aligned} 2\sqrt{D_z t} &= 12.86\ \mu m \\ D_z &= 2 \times 10^{-8}\ cm^2/hour \; . \end{aligned}$$

As predicted by the simplified diffusion model, the Ti concentration at the edge of the original Ti-film was half of the concentration at $Z = -\infty$. The Ti concentration was down by another factor of 2 at position about 6 μm from the edge. We concluded that the lateral spread of 70 μm channel guide was about 6 μm on each side and enhanced lateral diffusion is not observed in this study. This conclusion was further supported by the results of optical waveguiding profile measurement of He-Ne laser light propagating in a 4 μm wide channel waveguide.

V. PLANS FOR THE NEXT QUARTER

We have achieved the goal of 80% total throughput of one expansion and one contraction curved taper structure. The cross-talk between two crossed channel waveguides will be studied in a quantitative way. The fabrication of interdigital electrodes is under way at the photolithographic services of Hughes Aircraft Company, Fullerton, California. A Bragg deflector will be integrated with the crossed channel waveguides immediately upon receiving the photomask. As of the last step of experimental phase, the evaluation of the final integrated optical device is expected to be carried out early in the next quarter.

A boule of $LiTaO_3$ has been sliced, polished and is now ready to be processed. Switching devices will also be fabricated and tested in this material which can handle much higher optical power densities without waveguide damage.

VI. SUMMARY

During the third quarter of this program, the measurement of single mode coupling efficiency for linear tapers of four different taper lengths was continued. For TM wave propagation, the coupling efficiency was much lower than for TE wave propagation. The difference in coupling efficiency was due to the presence of Li_2O out-diffusion waveguide modes, which occurred only when the TE mode was excited in Ti-diffused channel guide. Because the throughput of linear tapers for both TE and TM waves were not as high as the 90% required throughput, several design modifications were made. Instead of expanding the 4 μm channel waveguide to 70 μm width, a lower value of 30 μm was used. The linear taper was also replaced with a curved horn of three linear segments of different slopes with the attempt to maximize the coupling efficiency for a fixed coupling length. The channel guide width is expanded from 4 μm to 10 μm by the first linear taper of length 200 μm, from 10 μm to 20 μm by the second linear taper of length 500 μm, and from 20 μm to 30 μm by the third taper of length 800 μm. The full angles of these tapers are 1.72°, 1.15°, and 0.72° respectively. To ensure an efficient Bragg deflection between two channel waveguides intersecting at the Bragg angle, the grating periodicity was reduced from the original design of 7.0 μm to 4.0 μm. This 4 μm spacing grating is readily achieved by conventional photolithography. The preliminary experimental results of the new taper waveguides indicate that a single mode to single mode coupling efficiency of 90% per taper for TM waves has been achieved.

The coupling efficiency of a given taper structure depends strongly on the expansion ratio of the channel width (final width to initial channel width). So it is important to know the amount of lateral diffusion which proceeds simultaneously with the downward diffusion. We have studied the Ti concentration profile near the edge of a strip of 70 μm initial width using electron microprobe technique. The lateral spread of this 70 μm wide channel guide was about 6 μm on each side. We concluded that enhanced lateral diffusion was not observed in this study.

REFERENCES

1. B. Chen and G. Tangonan, "Thin Film Optical Switch," Midterm Report, Contract N00173-76-C-0113, September 1976.

2. R.K. Winn and J.H. Harris, IEEE Trans. Microwave Thoery Tech., MTT 23, 92 (1975).

3. W.K. Burns, A.F. Milton, and A.B. Lee (to be published).

4. J.M. Hammer, W. Phillips, and C.C. Neil, "Channel Waveguide Study," Contract N00014-75-C-0078, January 1976.